



Search for gamma-ray sources near the Galactic Center.

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**On behalf of the Fermi-LAT
Collaboration**

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INTRODUCTION

- Several groups have demonstrated the existence of an excess in the gamma-ray emission around the Galactic Center (GC) with respect to the predictions from a variety of Galactic Interstellar Emission Models (IEMs) and point source catalogs (see e.g. Hooper et al. 2010, Calore et al. 2014 and Ajello+ 2016).
- Bartels et al. (2015) and Lee et al. (2015) have investigated the GC excess and suggest that it comes from a population of unresolved pulsars (PSRs).
- A fraction of these faint sources should be detected with future Fermi-LAT catalogs (e.g. Bartels et al. 2015 and Hooper et al. 2014).
- Providing a list of point sources in the GC is important to confirm or exclude the pulsar interpretation and to model the GC excess (see Prof. Bloom's presentation).

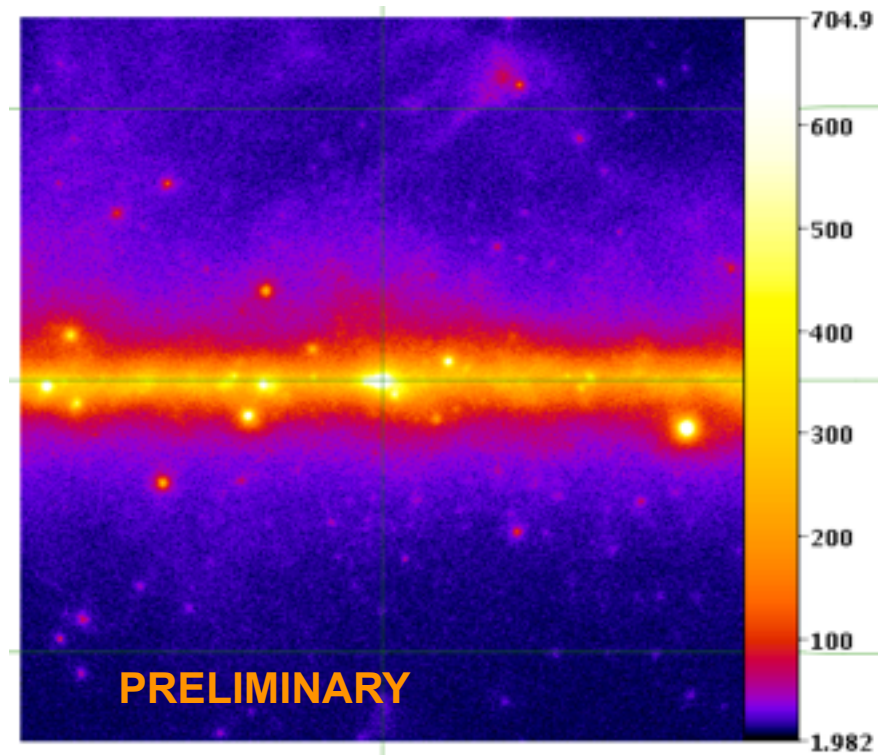
GOALS

- Find sub threshold ($TS < 25$) source candidates (seeds) with respect to the 3FGL catalog.
- Derive the list of seeds for different IEMs.
- Verify if faint seeds are real sources or structured residuals with respect to the IEM.
- Provide a ranked list of pulsar candidates that can be studied with radio timing searches.
- Test the PSR vs the DM interpretation as the origin of the GC excess.

Analysis details

- We use **Fermipy**: a python package that automates Science Tool (ST) analysis (<http://fermipy.readthedocs.org/en/latest/index.html>). See Matthew Wood's presentation for additional details.
- We consider a **40x40 deg** region centered around the GC. This region is divided into **64 ROIs** and the analysis is done in each independently.
- Each ROI is **8x8 deg²** and has an overlap of 3 degrees with the adjacent ROIs. Pixel size: **0.06deg**, energy bins: **8 bins per decade**.
- **74 months** of Pass 8 SOURCE data.
- We use the **E=[0.3,500] GeV** energy range and we make some tests also for **E=[0.5,500] GeV** and **E=[1,500] GeV**.
- We use **two different IEMs**:
 - Official Pass 8 template: **gll_iem_v06.fits** (**OFFICIAL (Off)**)
 - Reference model of the Pass 8 GC analysis (**REFERENCE (Ref)** see Prof. Bloom's presentation).

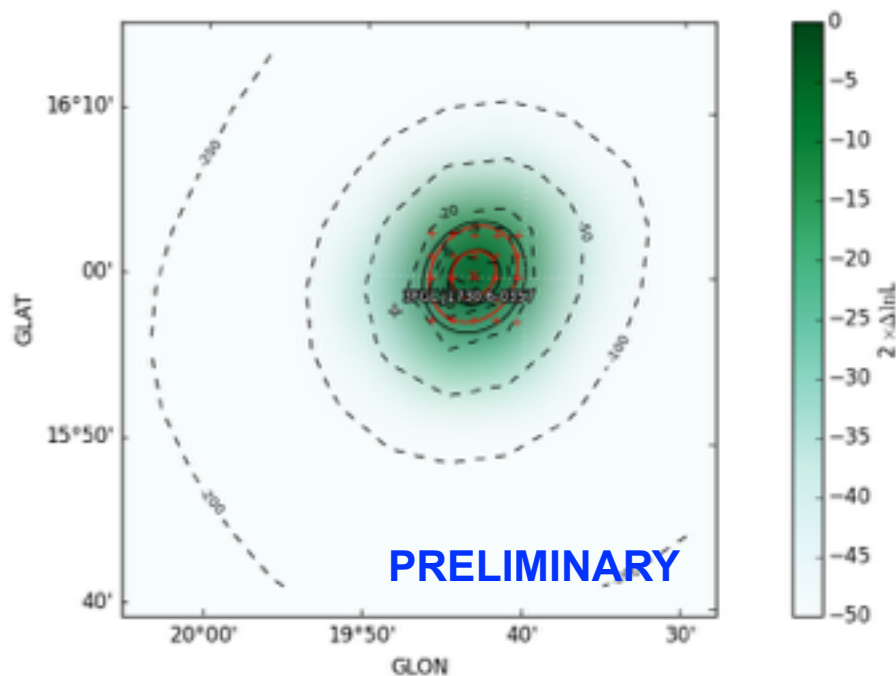
Count map for **E=[0.3,500] GeV**



Analysis Pipeline

Analysis Pipeline 1

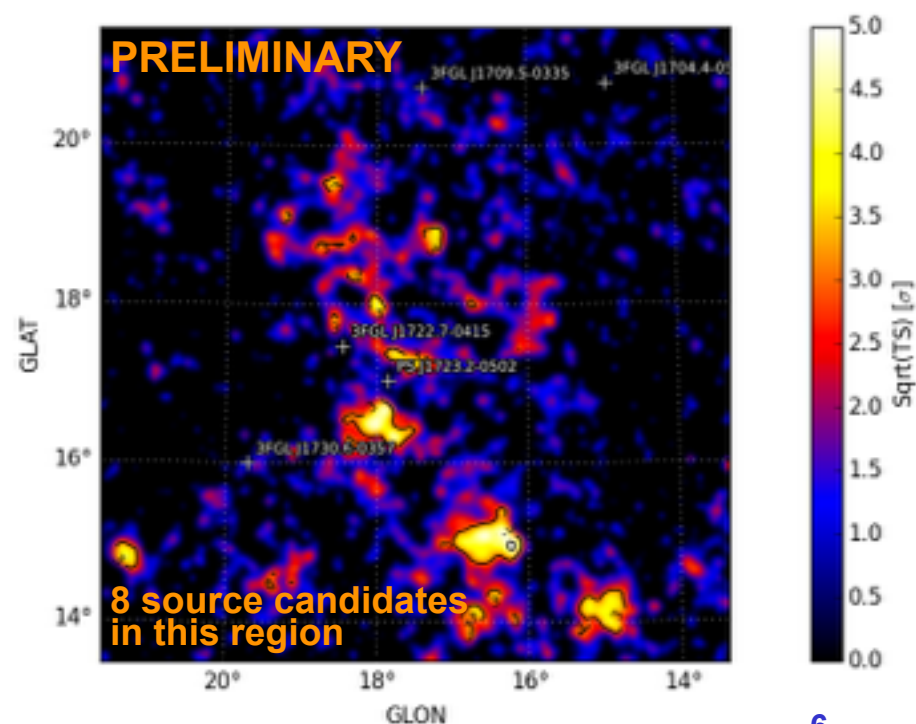
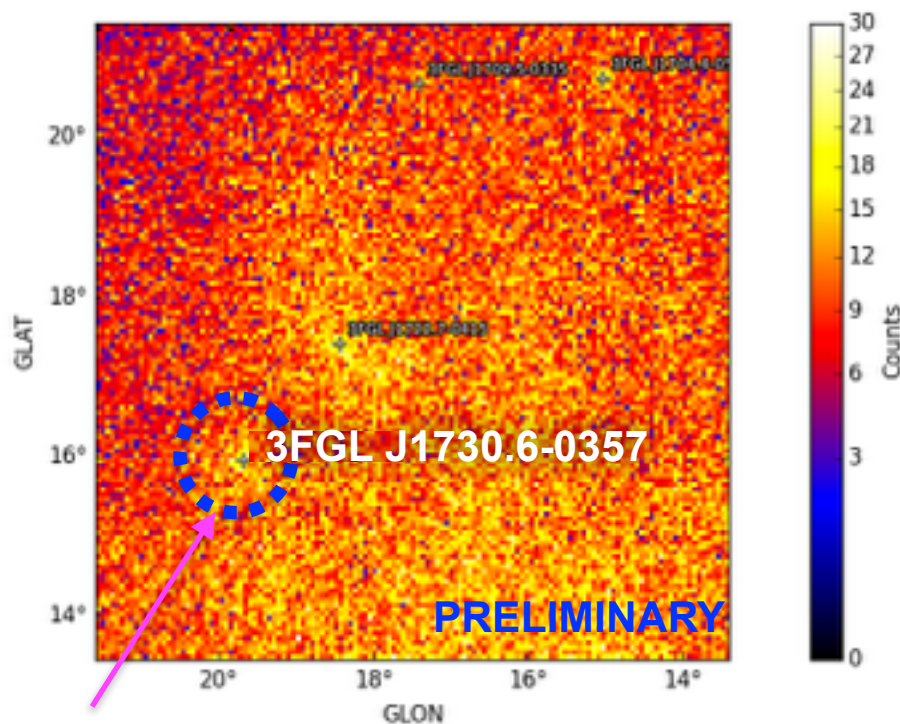
- We illustrate the pipeline, reporting results for **ROI_0** (glon=17.5deg and glat=17.5deg).
- Fermipy first applies to the ft1, as usual for the binned analysis with ST, the following tools: **gtselect**, **gtmktime**, **gtbin**, **gtsrcmap**.
- The initial model contains 3FGL sources with TS>49, the **IEM** and the **isotropic template**.
- We use the *fermipy.localize* module for relocalizing and to find the spectral properties of 3FGL sources.



- Localization is performed in two steps. First a TS map is computed centered on the source.
- A fit is then performed to the maximum TS peak in this map. The source position is then further refined by scanning the likelihood in the vicinity of the peak found in the first step.
- **3FGL J1730.6-0357** position is refined with an offset of 0.0874 deg and with **68% containment radius= 0.025 deg** (as a comparison in 3FGL is **0.049 deg**).

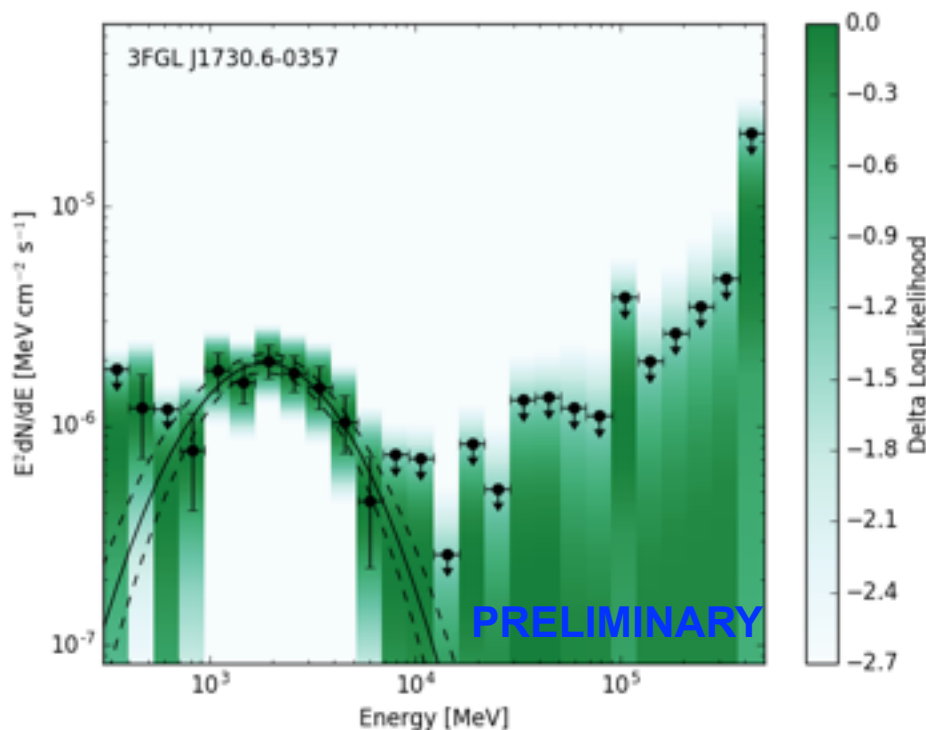
Analysis Pipeline 2

- Then with three iterations we include in our source model fainter point sources.
 - First step:** We extract new source candidates from the TS map (*fermipy.source_find* module with `sqrt_ts_threshold=8.0`, `min_separation=0.5`). We include the new sources in the model and make a fit of the roi with the *GTAAnalysis.fit* function of Fermipy. Then we optimize the roi with *GTAAnalysis.optimize*.
 - Second step:** We make the same we have done in Step 1 but using `sqrt_ts_threshold=6.0`, `min_separation=0.4`.
 - Third step:** The same as before with `sqrt_ts_threshold=4.0`, `min_separation=0.3`.



Analysis Pipeline 3

- We now derive the **SED** of each source in the ROI with $TS > 25$ using the *fermipy.sed* module.
- Spectral Likelihood profiles:** Bin-by-bin likelihood calculated by scanning the energy spectrum of the putative source. The color scale denotes the variation of the $\text{Log}(L)$ with respect to the best fit value of the putative source flux.
- We test different spectral shapes for the source: power-law (**PL**), power-law with exponential cutoff (**PLE**) and log-parabola (**LP**). We derive the TS for a curved spectrum with ($TS^{\text{PLE}}_{\text{curv}} = +2(\log L_{\text{PLE}} - \log L_{\text{PL}})$)



- In Roi_0 8 source candidates.
- The energy cutoff of 3FGL J1730.6-0357 is found to be **1400 MeV** and $TS^{\text{PLE}}_{\text{curv}} = 44$.
- This source is unassociated in the 3FGL.**

Source list results

Source List with Off and Ref. IEM

Analysis E and IEM	N($ b , l < 20^\circ$)	3FGL detection rate
E=[1,500] GeV Off	347	176/202
E[0.5,500] GeV Off	379	182/202
E=[0.3,500] GeV Off	413	189/202
E=[0.3,500] GeV Ref	443	182/202

Association with a 3FGL source: $d < \sqrt{R95_3FGL^2 + R95_cur^2}$. R95_3FGL 95% containment angle in the 3FGL while R95_cur in this analysis.

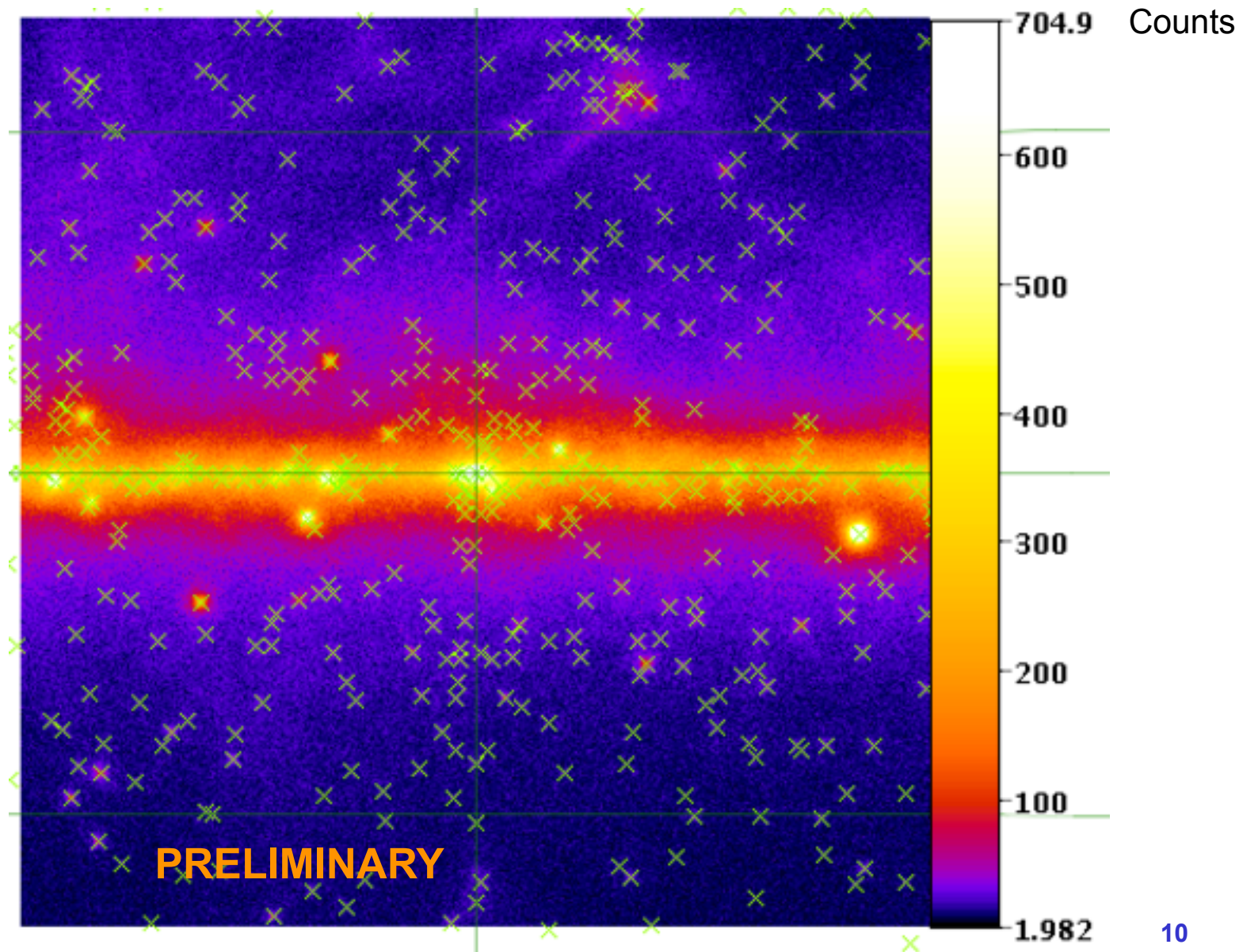
Sources present in E=[0.3,500] GeV Off list found also in E=[0.3,500] GeV Ref list.

1FIG (Ajello et al. 2016): 47 sources with $TS > 25$ in a $15 \times 15 \text{ deg}^2$ region around the GC and for E=[1,100] GeV: **80%** of FIG sources found also in our list.

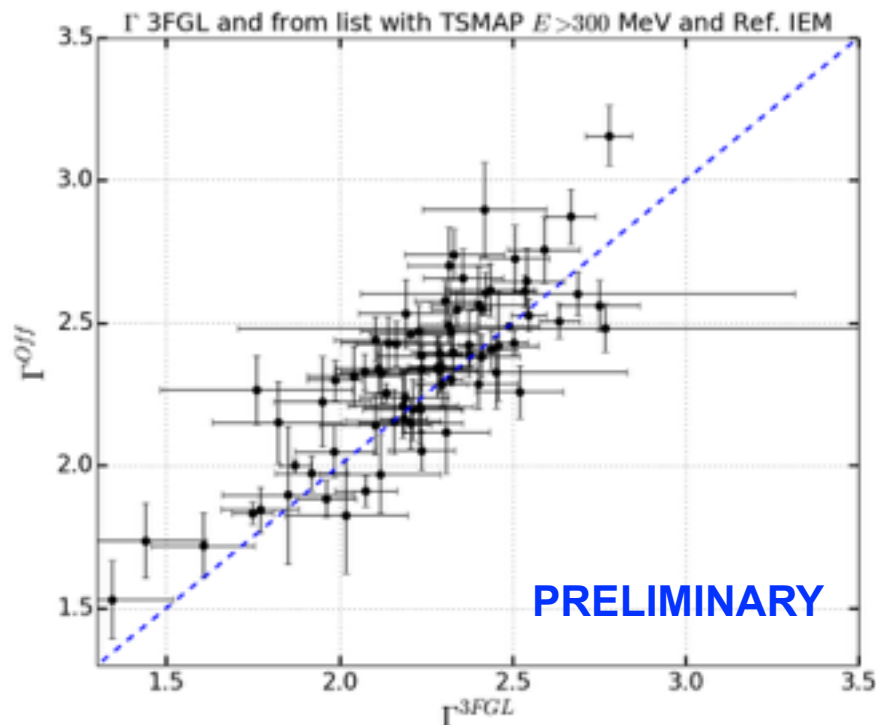
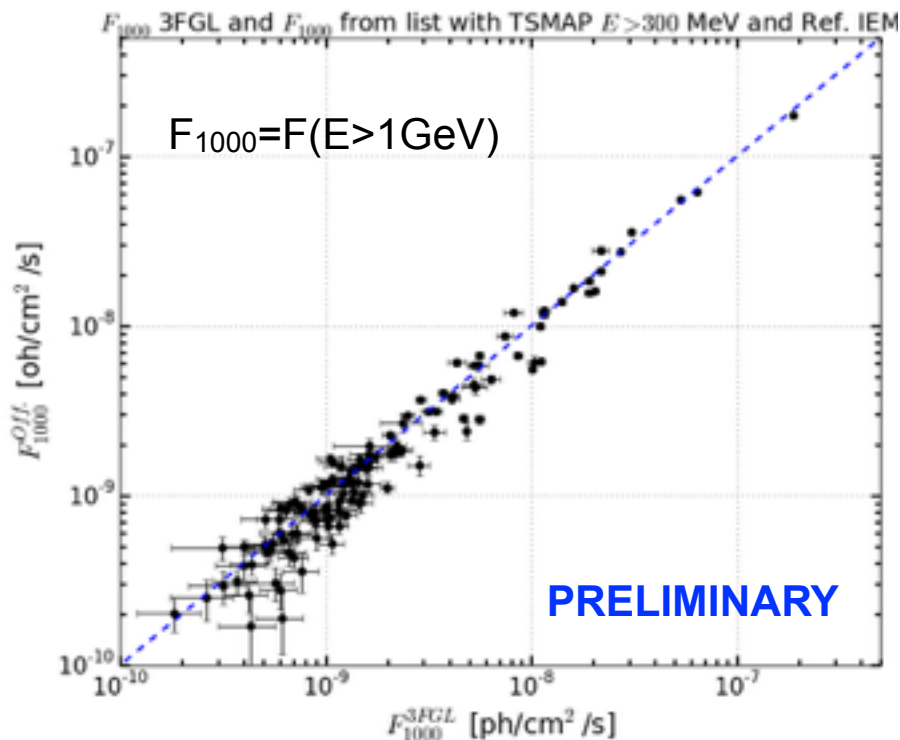
TS>	Correlated
25	80%
50	87%
100	90%

Missed sources: low TS objects ($TS = [25, 40]$) or sources located in a cluster of sources \rightarrow those are probably spurious point sources (extended sources or defects in the diffuse emission model).

Source Map for Off IEM and $E=[0.3,500]\text{GeV}$

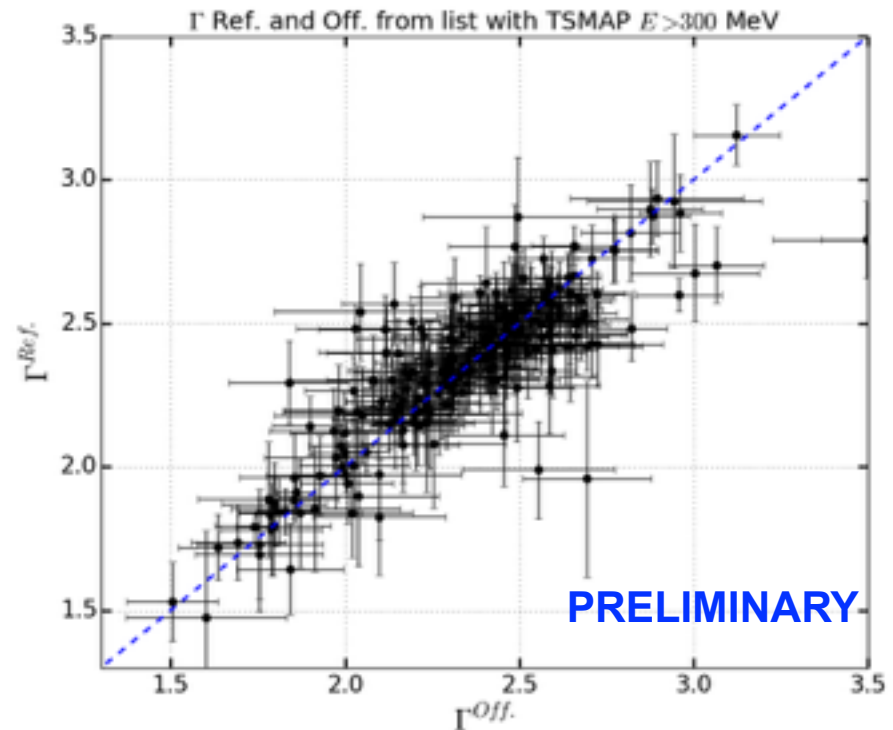
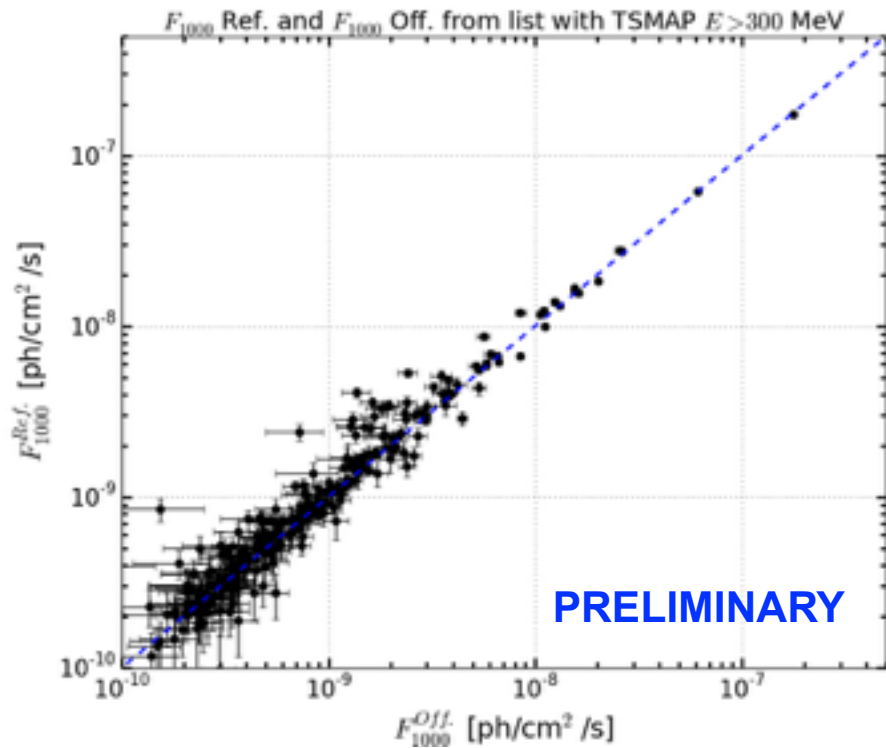


Gamma-ray spectrum 1 (comparison with 3FGL)



- The compatibility between the photon flux above 1 GeV from the 3FGL and from our analysis is good.
- The photon index above 100 MeV (Γ) in our analysis is softer with respect to the 3FGL because the 3FGL starts from 100 MeV (our analysis starts from 300 MeV).

Gamma-ray spectrum 2 (Off vs Ref IEM)

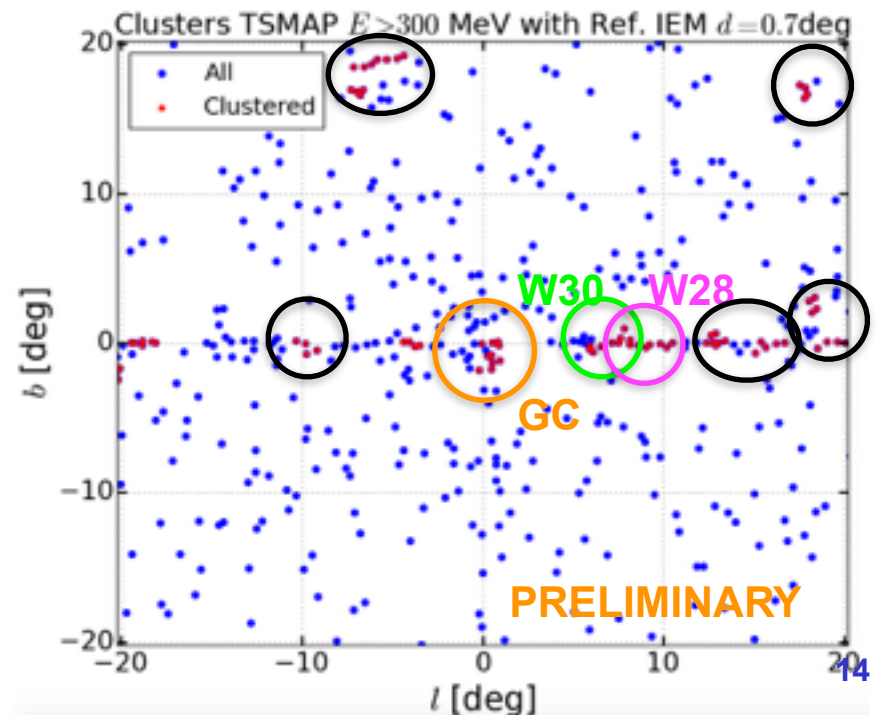
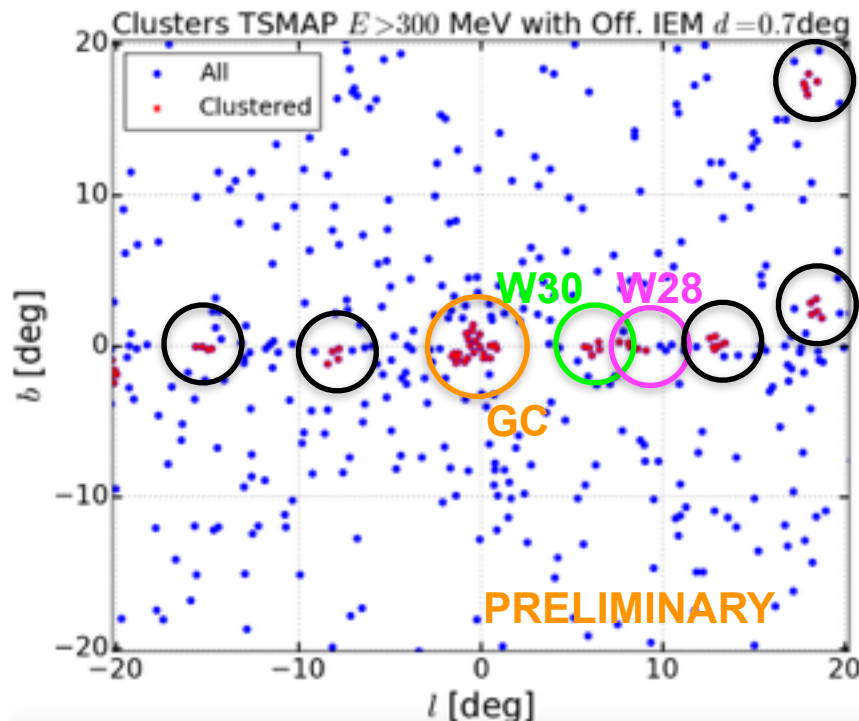


- The compatibility between the photon fluxes ($E > 1$ GeV) found with our analysis with Ref or Off IEM, is good.
- The same applies also for the comparison of photon indexes.

Point sources vs residual wrt the IEM

Clustering of sources (Minimum Spanning Tree)

- The minimum spanning tree (MST), which connects all the source locations together with the minimal total weighting for its edges, is the method that we use to find seeds that are very near to each other and that thus likely belong to the same source or residual with respect to the IEM.
- The MST method is implemented in *fermipy-cluster-sources* script that can be used with different values of the **dist [deg]** parameter.
- We apply the MST method to find cluster of sources using different values of the *dist* parameter.
- Cluster of seeds are found mainly on the Galactic plane.
- The templates we are using for **W30** and **W28** should be probably changed and sources found around the **GC** are associated to some extended residual (the GC excess).



SED of gamma-ray pulsars vs blazars

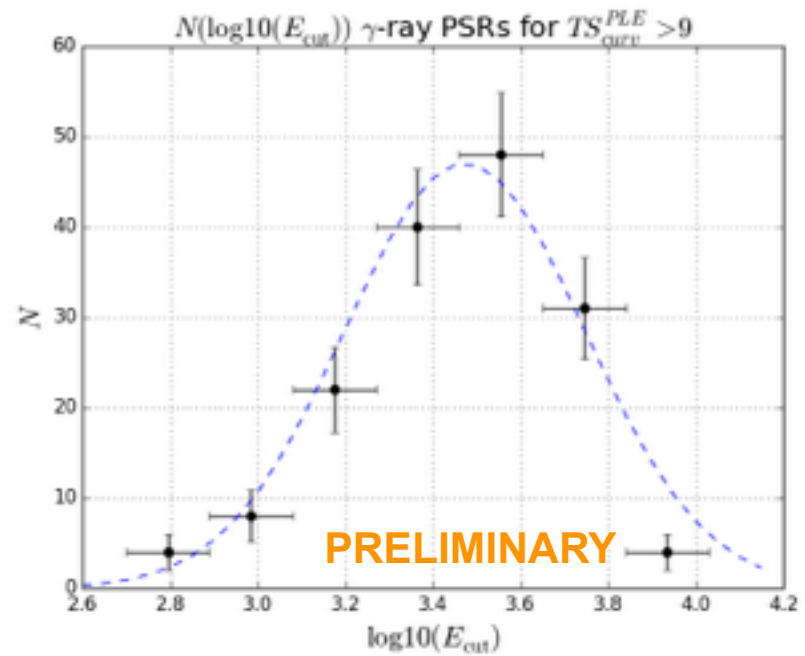
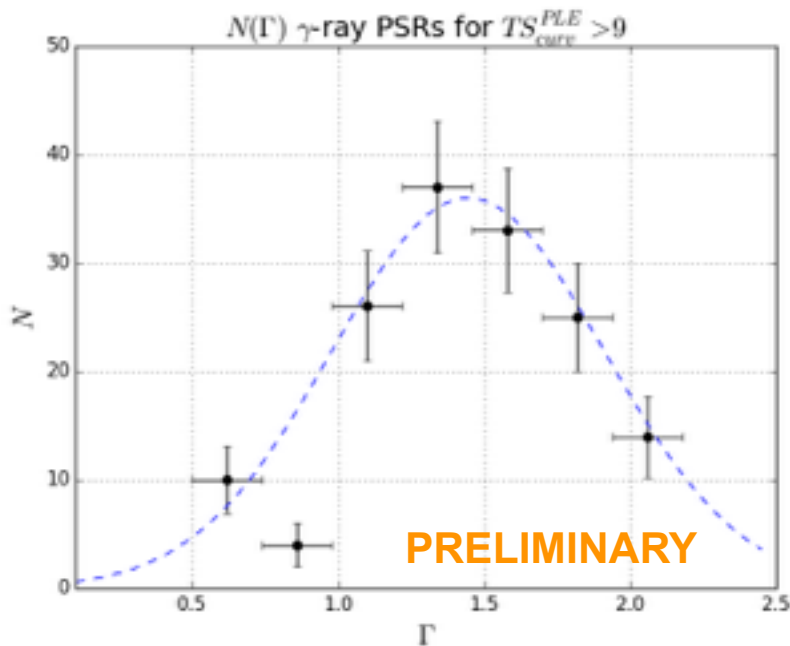
SED of gamma-ray pulsars

- 210 pulsars have been detected in gamma rays by the LAT.
- We studied the SEDs of those objects to find the average properties of PSR spectra.
- These properties will be used to select PSR candidates in the GC region.
- We put in the source model the 3FGL sources and we make a fit using only those sources and the IEM and isotropic template.
- We employ the same analysis used before for **$E=[0.3,500]$ GeV** where the final result is the SED of pulsars.
- In our sample of **210** pulsars: **172** have a curvature (**$TS^{PLE}_{curv} > 9$**) and **38** have **$TS^{PLE}_{curv} < 9$** .

Photon index and energy cutoff distributions

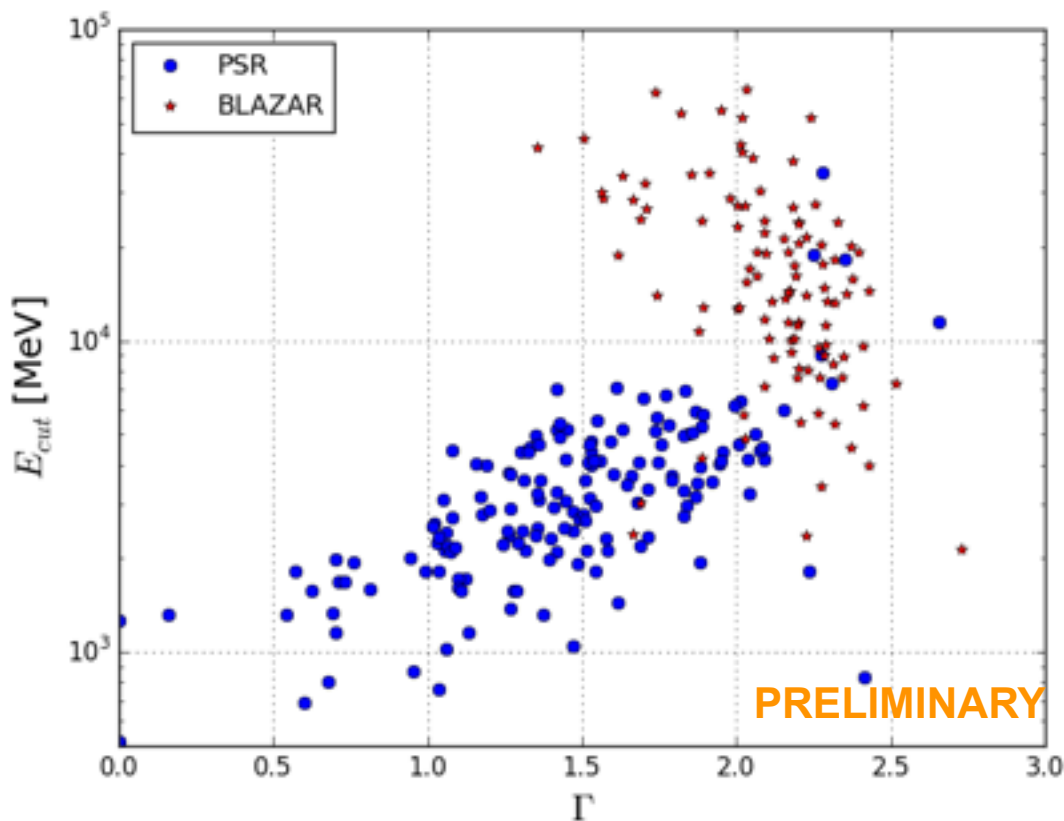
$TS_{\text{curv}}^{\text{PLE}} >$	Γ	$\text{Log10}(E_{\text{cut}}[\text{MeV}])$	$N_{\text{pul}}(TS_{\text{curv}}^{\text{PLE}} >)$
9	1.44 ± 0.47	3.47 ± 0.27	82%
16	1.40 ± 0.46	3.44 ± 0.24	74%
25	1.40 ± 0.47	3.44 ± 0.25	66%

$$\frac{dN}{dE} = K \left(\frac{E}{E_0} \right)^{-\Gamma} \exp \left(-\frac{E}{E_{\text{cut}}} \right)^b \quad b \text{ fixed to 1}$$



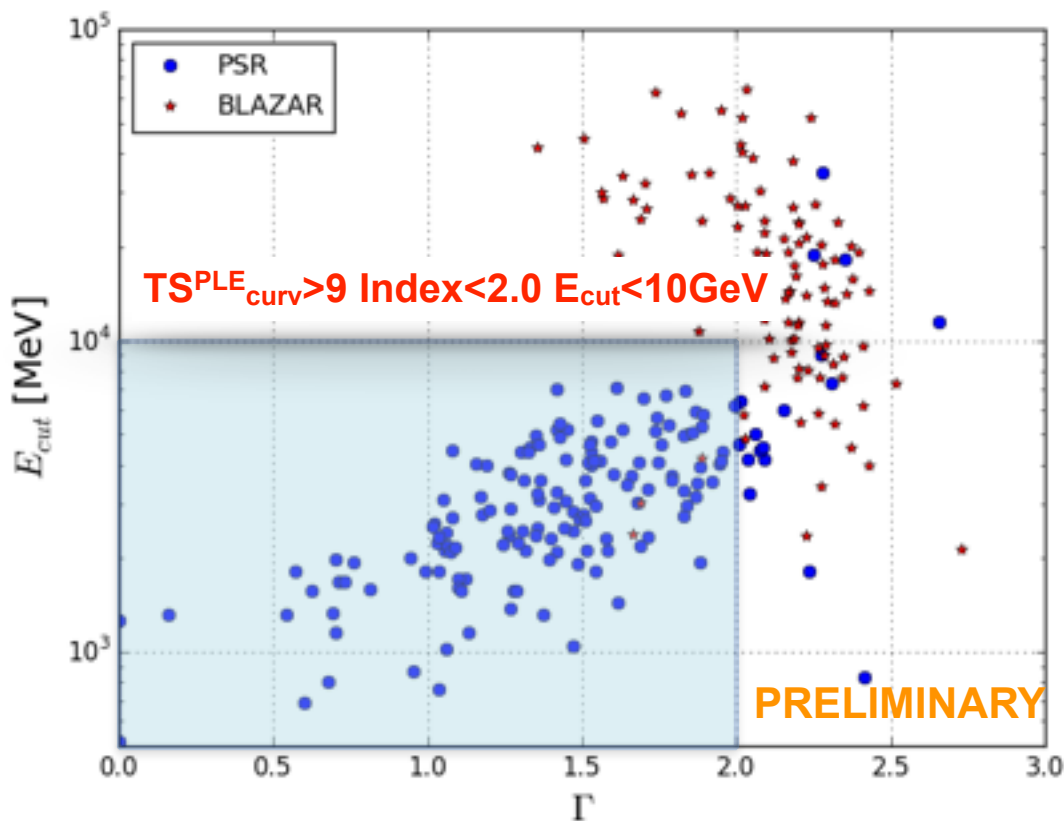
SED OF 3FGL BLAZARS WITH $TS^{3FGL}_{curv} > 9$

- We selected 3FGL blazars with $TS^{3FGL}_{curv} > 9$ (TS^{3FGL}_{curv} is the TS of curvature as given in the 3FGL).
- For this sample of 170 blazars we study the SED testing different spectral shapes: PL, PLE, LP.
- 116 of these blazars have $TS^{PLE}_{curv} > 9$.



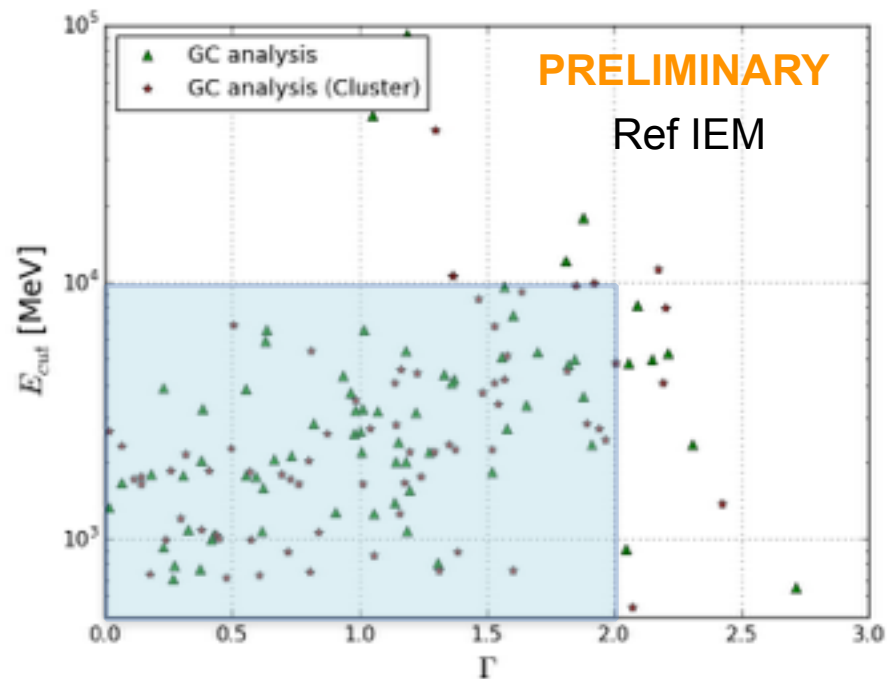
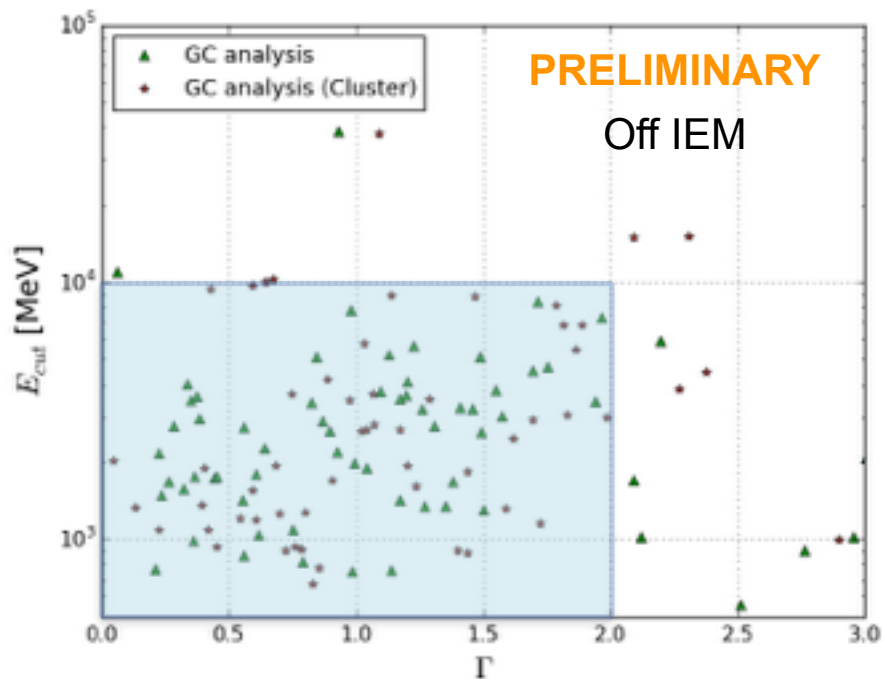
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- For this sample of 170 blazars we study the SED testing different spectral shapes: PL, PLE, LP.
- 116 of these blazars have $TS^{PLE}_{curv} > 9$.
- **We find only 3 blazars with $TS^{PLE}_{curv} > 9$, Index < 2.0 and energy cutoff $< 10\text{GeV}$!**



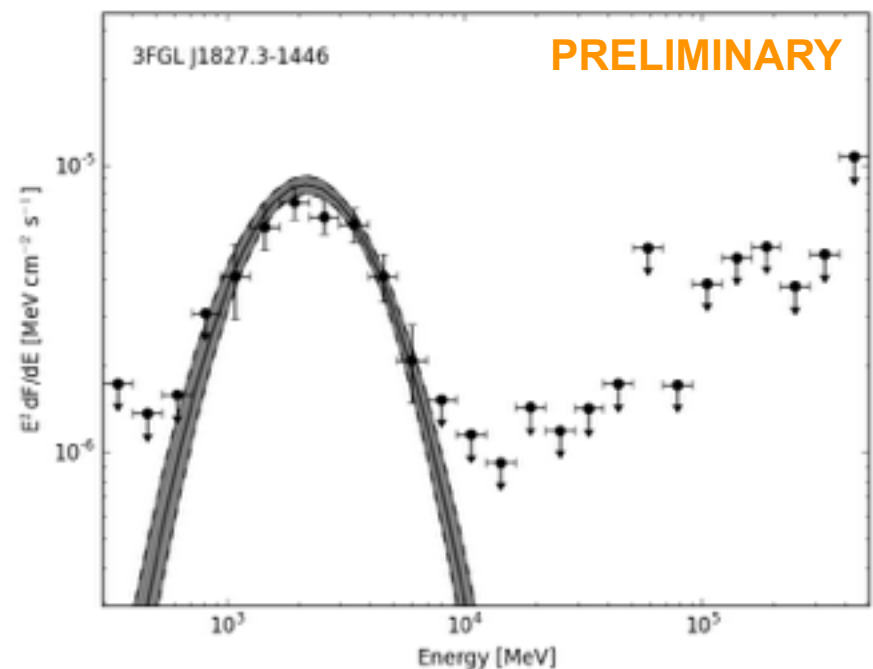
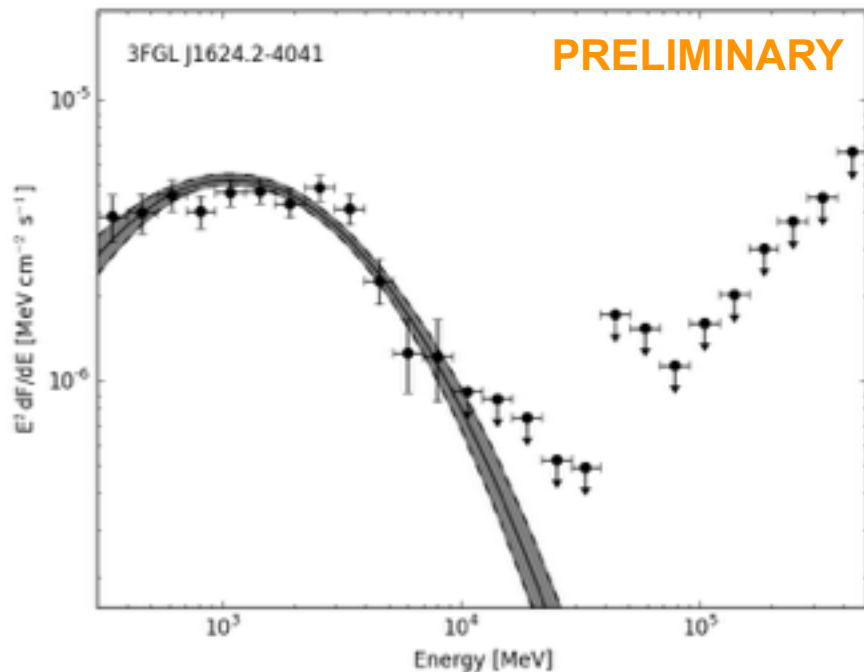
PSR Candidates

- We select source candidates, new with respect to the 3FGL or unassociated in the 3FGL, with **$\text{TS}^{\text{PLE}}_{\text{curv}} > 9$, $\text{Index} < 2.0$ and energy cutoff $< 10 \text{ GeV}$.**
- Using this criterion we find **88** PSR candidates using both **IEMs**.
- We derive for those candidates harder indexes ($\Gamma = 1.11 \pm 0.58$) while the cutoff energies are similar to what we have for already detected PSRs ($\log_{10}(E_{\text{cut}}[\text{MeV}]) = 3.37 \pm 0.29$).



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- **Recently announced to be pulsars by the Einstein@Home survey for gamma-ray pulsars!!!** https://einsteinathome.org/gammaraypulsar/FGRP1_discoveries.html



RESULTS

- We used the *Fermipy* tool to derive a list of source candidates near the GC.
- We tested this list with two different IEMs.
- Using $TS_{>25}$ we create a list of more than 400 seeds using $E=[0.3,500]$ GeV for a region **40x40 deg² around the GC**
- We derive the PSR SED properties to identify among those seeds promising PSR candidates.
- Using the criterion **$TS^{PLE}_{curv}>9$, $Index<2.0$ and $E_{cut}<10\text{GeV}$** we created lists of PSR candidates.
- We find 88 seeds with PSR-like SEDs found with both IEMs which could be the brightest exemplars of a bulge PSR population.

NEXT STEPS

- We will derive the average PSR SED to improve on the pulsar classification criterion.
- Test with simulations:
 - Calibrate a parameter to be used in a ranked list of candidates.
 - Find the (l,b) efficiency for the detection of PSRs for a bulge population of objects
- Include in the analysis the weighted Likelihood (it includes the uncertainty due to the IEM).
- Compare the PSR and DM hypothesis using the TS distribution of our seeds.